This paper proposes an algorithm for substantiating the type and volume of redundant structural and functional elements of reconnaissance-firing systems, taking into consideration the operational patterns of such systems. Underlying this algorithm is the combination of survivability assessment methods and reliability assessment methods. Such an arrangement aimed to improve the efficiency of the application of these methods and reduce uncertainty in the calculations.

The results from calculating an example of the application of a procedure for substantiating the type and volume of redundant structural and functional elements of reconnaissance-firing systems have been analyzed. The analysis of the results shows that the set task is fulfilled, in particular the specified probability of trouble-free functioning of a reconnaissance-firing system, with a combined type of redundancy. Moreover, it implies giving preference to passive redundancy, using active one only to critical elements – individual functional elements of the control subsystem. The advantage of a mixed type of redundancy over a passive redundancy is 28 %. In addition, it has been established that the multiplicity of redundancy, for accepted conditions, should not be lower than 2. A procedure for substantiating the type and volume of redundant structural and functional elements of reconnaissance-firing systems has been devised, taking into consideration the operational patterns of such systems. The specified procedure includes an algorithm, as well as methods for assessing survivability and methods for assessing the reliability of functioning. This procedure was tested for feasibility by considering an example of justifying the type and volume of redundant structural and functional elements of reconnaissance-firing systems that produced an adequate result. The result has been confirmed by the practical application of reconnaissance-firing systems in recent armed conflicts

Keywords: reconnaissance-firing systems, survivability, reliability scheme, structural and functional scheme

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DEVISING A PROCEDURE FOR SUBSTANTIATING THE TYPE AND VOLUME OF REDUNDANT STRUCTURAL-FUNCTIONAL ELEMENTS OF RECONNAISSANCE-FIRING SYSTEMS

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1. Introduction

The results of analyzing military conflicts in recent decades [1–4] indicate an increase in the share of combat missions aiming to defeat targets by reconnaissance-firing systems (RFS). The advantages of these systems are obvious: reaction speed, the accuracy of missions accomplished, mobility, stability of functioning. However, the increase in

the weight of these systems increases the volume of measures to counteract them [3–5].

The essence of the "paradoxical logic of war" [6] is that the more effective the sample of weapons, the more efforts are made to neutralize it. That is, the greater the role of RFS in the fight, the more efforts are given to combat them. In other words, the better the performance of RFS, the less the stability of its functioning, which, in turn, would lead to a decrease in its efficiency in general.

Certain measures are carried out to improve the ability of complex military systems to function under conditions of failure. Thus, planning military (combat) activities always accounts for the so-called permissible level of losses, that is, it is planned that some military units would lose their functional capabilities. Accordingly, redundant forces and capabilities are planned to maintain the ability to function. Quite often, the military literature argues about 10 % of the redundancy. Is this amount of redundancy enough? Is it necessary to reserve only forces and means? What type of redundancy should one use?

It is clear that under conditions of uncertainty and limited planning time it is difficult to calculate the volume of the redundancy. However, if one formalizes the specified process through the development of a procedure involving certain procedures, input data, and an algorithm, such a calculation could be simplified.

That is, one of the issues related to using RFS is the lack of effective mechanisms for determining the amount of redundancy depending on the operating conditions of these systems.

Moreover, different conditions of RFS operation would differently influence the effectiveness of a certain type of redundancy. In general, two main types of redundancies are considered – active and passive. An active redundancy implies a reserve containing one or more redundant elements that are under the main element mode [7]. A passive redundancy consists of one or more redundant elements that are in a passive state before they perform the functions of the main element [7].

Thus, the use of passive redundancy at critical points is due to a certain time of introduction, in case of failure, of the redundant element. This may cause tasks to be disrupted. On the other hand, it was confirmed that the effectiveness of active redundancy is slightly lower than passive redundancy. And when combining these types of redundancy in different areas of the organizational and functional chain, it is impossible to determine how much and what type of redundancy should be applied. That is, it is impossible to determine the amount and type of redundancy to achieve the desired level of probability of trouble-free operation.

In addition, when determining the probability of trouble-free functioning of RFS, it is impossible to take into consideration the structural and functional association of individual functional elements from different subsystems (reconnaissance, control, firing). That is, with the same number of individual functional elements in RFS, the probability of failure-free functioning may be different. This is because different variants of organizational and functional combinations would have different survivability indicators. Accordingly, another issue is disregarding survivability in determining the reliability of RFS functioning and vice versa.

In general, approaches to ensuring the ability of RFS to function under conditions of military (combat) activities often include several measures that are not consistent with each other. Thus, the analysis of existing approaches reveals that the organizational and functional combination of individual elements is carried out separately for subsystems. Separately for the reconnaissance subsystem, separately for a control subsystem, separately for the firing subsystem [8]. Moreover, the survivability of these subsystems is usually determined without taking into consideration the reliability of operation [9, 10]. At the same time, the reliability of functioning is typically determined without taking into consideration the possibility of changing the structural and functional scheme [11–13]. That is, disregarding the survivability of this system.

Failure to agree on these measures in the practical aspect leads to a high level of uncertainty when planning the combat application of RFS. In particular, in determining the type and volume of redundant structural and functional elements of RFS. In other words, the inconsistency of measures to ensure the ability of RFS to operate under the conditions of military (combat) activities predetermines uncertainty in achieving the goal of the military (combat) operation in general.

Thus, the relevance of this scientific and applied problem is due to the need to develop effective mechanisms for determining the volume and type of redundant structural and functional elements of RFS with a comprehensive account of the survivability and reliability of the functioning of these systems. In addition, the relevance of this scientific and applied issue has been confirmed by the widespread use of RFS in modern military conflicts.

2. Literature review and problem statement

Paper [9] considers the issues of improving the effectiveness of measures to improve the survivability of military facilities, in particular through disguise. However, the paper does not cover the issue of combining increased survivability with increasing the reliability of the functioning of military facilities.

Article [10] addresses the issue of ensuring the survivability of forces and means of assault troops, in particular through the renewal of weapons and military equipment. However, the article does not consider such important measures to ensure the ability to fulfill missions as reserving capabilities.

Work [11] reports a procedure for assessing the effectiveness of the reliability of the functioning of an automated military system. The main difference between this procedure and others is that this procedure makes it possible for the relevant management bodies to determine its effectiveness. Moreover, determining it can be carried out in sync with the timing of the cycles of management of troops and means, taking into consideration the technique for managing control objects chosen in it. However, this procedure does not make it possible to determine the type and amount of redundancies to ensure the predefined probability of trouble-free operation within the specified period.

Article [12] proposes a procedure for assessing the reliability of the functioning of automated systems for managing troops (forces) using an example of the automated control system "Oreanda-PS". This procedure is based on considering the independence of the flow of failures of technical means on software failures, and vice versa. However,

the article does not consider the connection among subsystems that participate in the implementation of the missions set, in particular, the subsystems of intelligence, control, and firing.

Paper [13] reported a set of estimation ratios that helped perform a quantitative assessment of the benefit in terms of the reliability of systems at the joint use of structural, time, and load reservation. However, the paper did not consider a variant of combined reservation; the survivability of the system was disregarded.

Study [14] addresses the modeling and analysis of the reliability of complex systems that employ disposable elements during their operations. The study involves an analysis of the reliability of disposable items used affecting the resulting level of reliability of the system in general. However, the study does not take into consideration the structural and functional connections among individual functional elements that participate in the implementation of tasks.

Article [15] tackles the application of a variation gradient method to dynamic systems. Using a variation gradient method could increase the efficiency of information processing in the processes of management and research of dynamic systems. As an example of the model, the application of a variational gradient method to models of automated control systems for unmanned aerial vehicles is considered. However, the article does not address the issues of combining several approaches for assessing the functional stability of parameters.

Paper [16] considers the application of a modified gradient method to decision support systems to control an unmanned aerial vehicle assigned by integrated-differentiation models with low nonlinearity. Based on the proven theorem, it is concluded that a given method converges. Convergence rate estimates are presented. The modified gradient method makes it possible to explore a wider class of dynamic models when considering the tasks to manage unmanned aerial vehicles. However, the cited paper does not describe the behavior of such systems when one includes redundant elements with different types of redundancies.

Work [17] describes the software implementation of a mathematical model of reliability of a renewable technical system with a constant active redundancy. The developed software automates the formation of the mathematical model of reliability in the form of a system of equations by Kolmogorov-Chapman and makes it possible to analyze the reliability indicators of the technical system for different multiples of redundancies. However, the work does not consider the procedure for choosing the type of reservation.

Paper [18] proposes an approach to improving the reliability of complex technical systems by synchronizing ADS-B receiver systems (Automatic Dependent Surveillance-Broadcast) using MLAT (MultiLATeration) technologies. The essence of MLAT technology is that a system of several receivers (at least three) can measure the coordinates of an air object, even under conditions when the air object does not transmit information about its location to space. ADS-B is a technology in which "each aircraft sees another", which allows pilots to prevent dangerous situations [18]. However, the paper does not consider the possibility of combining various methods to increase the reliability of functioning.

Thus, the basic disadvantages of existing approaches are the high complexity of computations, not taking into consideration survivability in the assessment of reliability, and vice versa. In addition, the identified shortcomings include the impossibility of justifying the choice of the type and volume of redundant individual functional elements, a high level of uncertainty in the selection of input data. The essence of this study's scientific problem is predetermined by the identified shortcomings, which imply the lack of a scientific and methodological apparatus to substantiate the type and volume of redundant structural and functional elements of RFS.

3. The aim and objectives of the study

The aim of this study is to devise a procedure for justifying the type and volume of redundant structural and functional elements of reconnaissance-firing systems, taking into consideration the operational patterns of such systems. This could make it possible to make informed decisions on the allocation of such a volume and type of redundant individual functional elements that would ensure the accomplishment of combat missions.

To achieve the set aim, the following tasks have been solved:

– to develop an algorithm for substantiating the type and volume of redundant RFS structural and functional elements;

– to devise a procedure for determining the type and volume of redundant RFS structural and functional elements.

4. Materials and methods to study the process of the substantiation of the type and volume of redundant structural and functional elements of reconnaissance-firing systems

Microsoft Excel 2010 (Microsoft, USA) was used for our calculations.

To assess the stability of RFS functioning during a military (combat) activity, we applied methods from a reliability theory [19–21].

In particular, to calculate the operational stability of non-renewable RFS with the active redundancy of structural and functional elements, a method for calculating the probability of trouble-free operation of a non-renewable system with an active redundancy [19–21] was employed.

The initial data for this method are the total number of individual structural and functional elements (n), the failure intensity rate (λ), the duration of a military (combat) activity (RFS operation time) (t), the number of redundant elements (n_e).

A general view of the structural scheme of RFS reliability with the active redundancy of structural and functional elements is based on data from [19]; it is shown in Fig. 1.

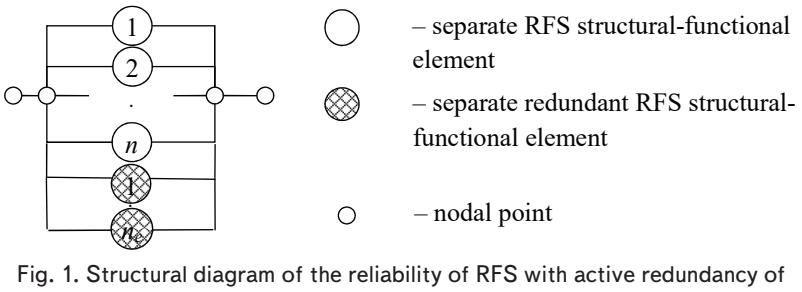

Fig. 1. Structural diagram of the reliability of RFS with active redundancy of structural and functional elements

Accordingly, the probability of trouble-free operation of RFS with the active redundancy of structural and functional elements is calculated from the following formula given in [17–19]:

$$P(t)_{r,ar} = 1-\left(1-e^{-\lambda t}\right)^{n_e+1}, \quad (1)$$

To calculate the functional stability of RFS with passive redundancy of structural-functional elements, we used a method for estimating the probability of the failure-free operation of a non-renewable system with passive redundancy [19, 20].

The initial data for this method are the same as for the method of calculating the probability of trouble-free operation of RFS with active redundancy.

A general view of the structural scheme of the reliability of RFS with passive redundancy of structural-functional elements is based on data reported in [19]; it is shown in Fig. 2.

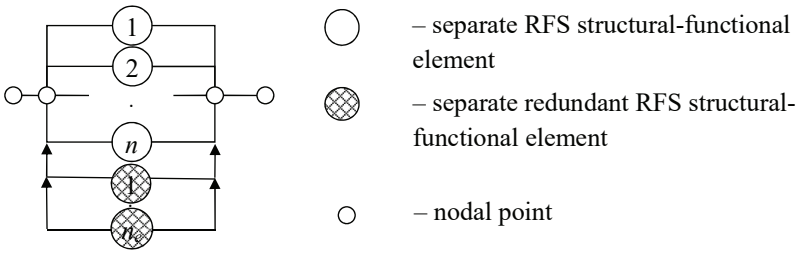

Fig. 2. Structural scheme of the reliability of RFS with passive redundancy of structural-functional elements

Accordingly, the calculation of the probability of the failure-free operation of RFS with passive redundancy of structural-functional elements is based on the following formula given in [19–21]:

$$P(t)_{r,pr} = e^{-\lambda t}\sum_{i=0}^{n_e}\frac{(\lambda t)^i}{i!}. \quad (2)$$

To assess survivability as a component of the stability of RFS functioning with various structural and functional schemes, a brute force method [20] is used. The essence of the method is to compare the performance coefficients of several structural and functional schemes by sequentially checking the system for survivability in case of the consistent failure of system elements. The application of this method could be visually represented in the form of a table of performance coefficients for two schemes (Table 1).

Table 1

Performance coefficients of RFS (for two schemes)

State No.	System element			Loss		Performance coefficient K_j	
	1	...	n	Scheme 1	Scheme 2	Scheme 1	Scheme 2
1	0		1	$l_{1.1}$	$l_{2.1}$	$K_{1.1}$	$K_{2.1}$
.	.	...	.	.	.	.	.
n_j	1	...	0	$l_{1,j}$	$l_{2,j}$	$K_{1,j}$	$K_{2,j}$

An indicator of RFS survivability under this method is the mathematical expectation of the number of working elements [20]:

$$M_s = \sum_{j=1}^{n} K_j P_j, \quad (3)$$

where M_s is the mathematical expectation of the number of working elements of the system; K_j is the performance coefficient of the system in the j-th state, it is determined from formula $K_j = \frac{n_{w,j}}{n}$ [20]; $n_{w,j}$ is the number of working elements of the system; n is the total number of the system's elements; n_j is the number of the j-states of the system; P_j is the probability of the j-th state of the system determined from the following formula given in [21]:

$$P_j = 1-C_n^l q^l (1-q)^{n-l}, \quad (4)$$

l is the number of simultaneous failures by the elements of the system; q is the probability of failure of the system element.

This study examines the generalized structural and functional scheme of RFS. That is, the use of the devised procedure is possible for any type of RFS, which has three subsystems (intelligence, control, firing). Moreover, the procedure provides for the possibility of taking into consideration the specificity of using RFS via changes in the values of indicators.

As regards the limitations, then, taking into consideration the specificity of RFS use (in particular during military (combat) activities), it can be accepted that RFS is not a renewable system.

Another constraint is to take into consideration those failures that are due to technical malfunctions and those caused by the enemy. That is, the failure rate would consist of two components. However, within the framework of the current study, it is proposed to take into consideration a single indicator – the intensity of failures.

It is also proposed to accept that the time of RFS operation is equal to the duration of a military (combat) activity.

Another limitation is that a failure flow is subject to the exponential law of random magnitude distribution and is the simplest.

5. Results of studying the process of substantiating the type and volume of the redundant structural and functional elements of reconnaissance-firing systems

5. 1. Developing an algorithm for substantiating the type and volume of redundant structural and functional elements of RFS

The input data for this algorithm are the number and intensity of failures of the structural and functional elements of subsystems, the time of operation (predicted), the predefined level of the probability of trouble-free operation, the number of possible structural and functional connections between individual elements of RFS.

At the first step of the algorithm, it is proposed to build the structural and functional schemes of RFS. In general, RFS consists of three subsystems – reconnaissance, control, and firing [22, 23]. However, despite their differing functional purposes, elements of these subsystems can be combined at the local level. This provides the ability to create different structural and functional schemes without

changing the number of individual elements and functional relationships.

In the next step, it is proposed to select a structural-functional scheme with the best survivability indicators. This choice is proposed to be carried out using the brute force method.

Structurally, this unit includes several subunits. These include the subunits for determining the performance coefficient of the system in a certain state, determining the probability of a certain state of the system, determining the mathematical expectation of the number of working elements of the system of a certain scheme using formula (3).

Moreover, determining a performance coefficient involves taking into consideration the RFS subsystems. In addition, the characteristics of subsystems are considered when determining the probability of a certain state of the system (4). Thus, both the number of individual functional elements in the reconnaissance subsystems (n_r), control (n_c), firing (n_f), and the intensity of their failures are taken into consideration: reconnaissance (λ_r), control (λ_c), firing (λ_f). Accordingly, the resulting probability of a certain state would be calculated from the following formula:

$$P_j = P_r P_c P_f, \quad (5)$$

where P_r is the probability of an intelligence subsystem being in a certain state; P_c is the probability of a certain state of the control subsystem being in a certain state; P_f is the probability of a firing subsystem being in a certain state.

In addition, this unit includes a subunit for checking the condition of compliance of the value of the calculated mathematical expectation with the assigned one. In the case when the calculated value is less than the specified value, they proceed to unit 3 to select another structural-functional scheme. Otherwise, they proceed to unit 8 to build reliability schemes according to the appropriate structural-functional scheme. The construction of such a scheme is carried out for areas depending on the characteristics of RFS use during activity.

The next step is the calculation of the probabilities of RFS failure-free functioning in accordance with areas with different types of redundancy using formulae (1), (2).

At the next stage, the resulting probability of RFS trouble-free functioning is calculated using the following dependence known from [19–21]:

$$P(t)_{r,res} = \prod_{\gamma=0}^{Z} P(t)_{r,\gamma}, \quad (6)$$

where γ is the number of the area of RFS reliability scheme with a certain type of redundancy; Z is the number of RFS reliability scheme areas with a certain type of redundancy.

Moreover, for areas with a serial connection between individual functional elements, the probability of trouble-free RFS functioning is determined in the way specified in [19–21]:

$$P(t)_{r,series} = \prod_{i=0}^{n} P(t)_{r,i}, \quad (7)$$

for connection in parallel [19–21]:

$$P(t)_{r,paralel} = 1 - \prod_{i=0}^{n} \left(1 - P(t)_{r,i}\right), \quad (8)$$

where γ is the number of the RFS reliability scheme area with a certain type of redundancy; Z is the number of the RFS reliability scheme areas with a certain type of redundancy.

The next unit checks the conditions if the resulting and specified RFS probability of a trouble-free functioning match. In the case when this condition is not met, it is necessary to proceed to change the scheme of RFS reliability. Otherwise, the algorithm proceeds to the unit that produces the results of calculations.

A general flowchart of the proposed algorithm for substantiating the type and volume of redundant structural-functional RFS elements is shown in Fig. 3.

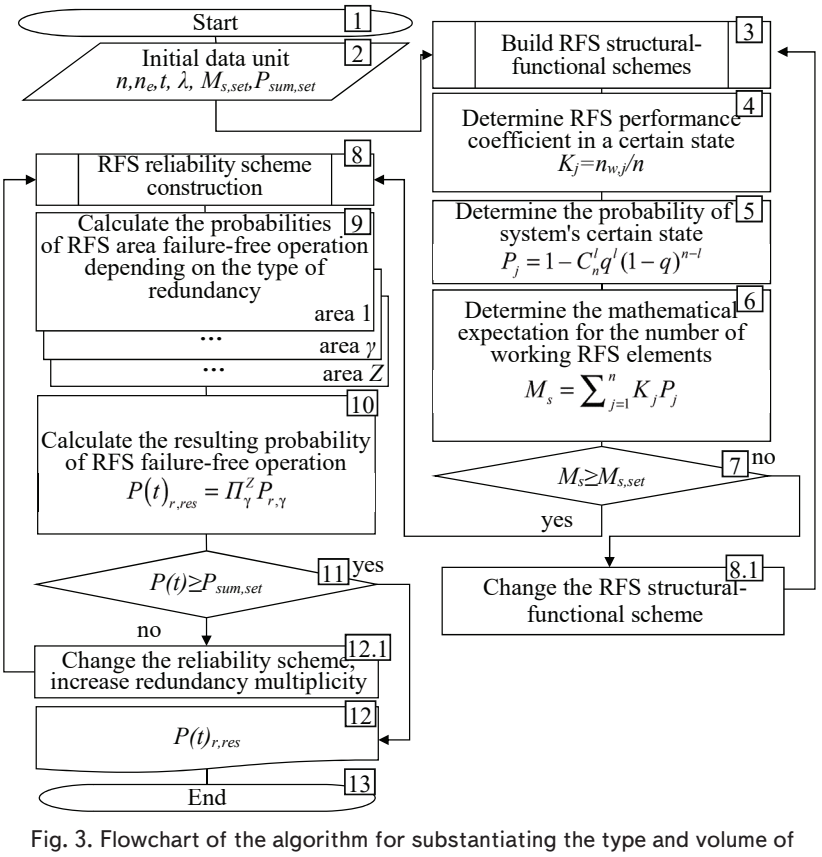

Fig. 3. Flowchart of the algorithm for substantiating the type and volume of redundant structural-functional elements of reconnaissance-firing systems

Thus, we have developed an algorithm for substantiating the type and volume of redundant structural-functional elements of RFS in the form of a flowchart (Fig. 3). This algorithm serves to substantiate the type and volume of redundant structural-functional elements of RFS, taking into consideration the operational patterns of such systems.

5. 2. Devising a procedure for determining the type and volume of redundant RFS structural-functional elements

The initial conditions for devising a procedure for determining the type and volume of redundant RFS structur-

al-functional elements for a single type of RFS under specific conditions of military activities include the following data: our troops, the enemy's troops, and the conditions of the situation.

The basis is an activity at the operational level.

Data for our troops to accomplish the RFS missions: the type of reconnaissance means – the unmanned aerial vehicles (UAVs) A1-SM "Furiya"; the number of UAVs, n_r=3; the number of redundant UAVs allocated by the senior chief, $n_{e,r}$=3. The type of control equipment is a hardware-software complex for the automated fire control of artillery unit "ArtOS"; the number of complexes, n_c=2; the number of redundant complexes allocated by the senior chief, $n_{e,c}$=2. The type of firing means is the 122-mm howitzer D-30; the number of howitzers, n_f=4; the number of redundant howitzers allocated by the senior chief, $n_{e,c}$=3.

Data on the enemy: the enemy has artillery systems in service: a 122-mm D-30 howitzer to the battery, a 152-mm howitzer D-20 to a platoon. The enemy's air defense means include a 23 mm anti-aircraft gun, ZU 23-2, to 2 units; the portable anti-aircraft missile systems "Ygla-1" 9K310, to 2 units. The means of electronic warfare: the automated interference station R-330Zh "Zhitel" – one unit. Generalization of data shows that the intensity of missions accomplished by the enemy could lead to the following intensity of failures to accomplish missions by available forces and reconnaissance means: λ_r=0.5; control, λ_c=0.2; firing, λ_f==0.5 failure/h.

Data depending on the situation: the generalized data indicate that achieving the goal of the activity to suppress enemy forces could take t=5 hours. Moreover, the number of missions that could be accomplished by RFS is determined on the basis of the established level of mathematical expectation of the number of working RFS elements $M_{s,set}$=5. In addition, to warrant the accomplishment of combat missions, the ability to perform tasks should be at least $P_{r,set}$=0.8.

At the first stage of devising the procedure, it is proposed to draw up the structural-functional schemes of RFS based on the initial data.

A general view of the RFS structural-functional schemes, built as an example of different variants, is shown in Fig. 4.

We used the brute force method (Table 1) to calculate the coefficients of performance for each state and each variant of RFS structural-functional schemes (Table 2) based on the initial data in an example.

Table 2

Results of determining the performance coefficients of schemes, Fig. 4, *a*–*d*

State No., j	System element									Number of simultaneous failures, l				Performance coefficient for schemes, K_j			
	Reconnaissance			Control		Firing											
	1	2	3	4	5	6	7	8	9	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
1	0	1	1	1	1	1	1	1	1	1	1	1	3	0.89	0.89	0.89	0.67
2	1	0	1	1	1	1	1	1	1	1	1	1	1	0.78	0.78	0.89	0.89
3	1	1	0	1	1	1	1	1	1	1	1	1	1	0.89	0.89	0.89	0.89
4	1	1	1	0	1	1	1	1	1	3	3	9	3	0.67	0.67	0	0.67
5	1	1	1	1	0	1	1	1	1	3	4	3	4	0.67	0.56	0.67	0.56
6	1	1	1	1	1	0	1	1	1	1	1	1	1	0.89	0.89	0.89	0.89
7	1	1	1	1	1	1	0	1	1	1	1	1	1	0.89	0.89	0.89	0.89
8	1	1	1	1	1	1	1	0	1	1	1	1	1	0.89	0.89	0.89	0.89
9	1	1	1	1	1	1	1	1	0	1	1	1	1	0.89	0.89	0.89	0.89

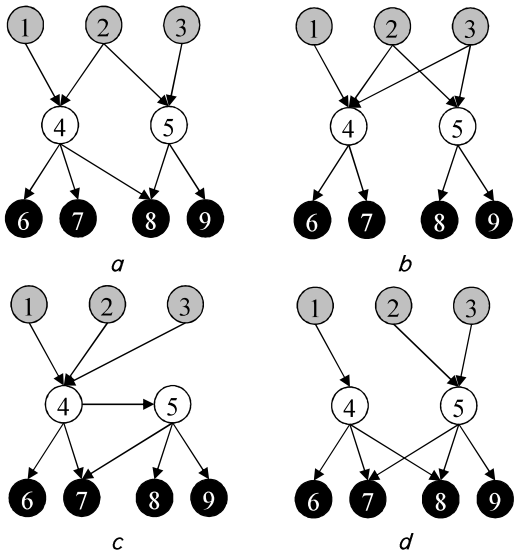

Fig. 4. The general view of structural-functional schemes of reconnaissance-firing systems built for different variants: *a* – focus on the subsystem of firing; *b* – focus on the intelligence subsystem; *c* – focus on functions at one control point; *d* – emphasis on the subsystem of firing; ○ – a separate functional element of the control subsystem; ● – a separate functional element of the firing subsystem; ● – a separate functional element of the intelligence subsystem

The probability of a certain state of the system is calculated from formula (4), separately for each subsystem (reconnaissance, control, firing). The calculation results are given in Tables 3–6.

Table 3

Results of determining the probability of a working state of the system for each subsystem according to scheme (*a*)

State No., j	Number of simultaneous failures, l	Probability of a working state of the system			
		Reconnaissance, P_r	Control, P_c	Firing, P_f	Resultant, P_j
1	1	0.98145	0.86466	0.99995	0.849
2	1	0.98145	0.86466	0.99995	0.849
3	1	0.98145	0.86466	0.99995	0.849
4	3	0.98145	0.53491	0.99797	0.524
5	3	0.98145	0.53491	0.99797	0.524
6	1	0.99945	0.86466	0.99797	0.862
7	1	0.99945	0.86466	0.99797	0.862
8	1	0.99945	0.86466	0.99797	0.862
9	1	0.99945	0.86466	0.99797	0.862

Note: The corresponding mathematical expectation of the number of working elements of RFS (3) is M_s=5.94

All proposed RFS structural-functional schemes meet the predefined condition. However, the best result is observed in scheme (*a*). Therefore, further calculations are performed relative to it.

A general view of reliability schemes for the conditions of the example with active (*a*), passive (*b*), and mixed (*c*) redundancies that we built is shown in Fig. 5.

We applied formulae (6) to (8) to construct a general estimation dependence for determining the probability of trouble-free RFS functioning for the reliability schemes shown in Fig. 5.

Table 4

Results of determining the probability of a working state of the system for each subsystem according to scheme (*b*)

State No., j	Number of simultaneous failures, l	Probability of a working state of the system			
		Reconnaissance, P_r	Control, P_c	Firing, P_f	Resultant, P_j
1	1	0.98145	0.86466	0.99995	0.849
2	1	0.98145	0.86466	0.99995	0.849
3	1	0.98145	0.86466	0.99995	0.849
4	3	0.98145	0.53491	0.99797	0.524
5	4	0.98145	0.53491	0.96594	0.507
6	1	0.99945	0.86466	0.99797	0.862
7	1	0.99945	0.86466	0.99797	0.862
8	1	0.99945	0.86466	0.99797	0.862
9	1	0.99945	0.86466	0.99797	0.862

Note: The corresponding mathematical expectation of the number of working elements of RFS (3) is M_s=5.93

Table 5

Results of determining the probability of a working state of the system for each subsystem according to scheme (*c*)

State No., j	Number of simultaneous failures, l	Probability of a working state of the system			
		Reconnaissance, P_r	Control, P_c	Firing, P_f	Resultant, P_j
1	1	0.98145	0.86466	0.99995	0.849
2	1	0.98145	0.86466	0.99995	0.849
3	1	0.98145	0.86466	0.99995	0.849
4	9	0.22659	0.60042	0.29008	0.039
5	3	0.99945	0.53491	0.96594	0.516
6	1	0.99945	0.86466	0.99797	0.862
7	1	0.99945	0.86466	0.99797	0.862
8	1	0.99945	0.86466	0.99797	0.862
9	1	0.99945	0.86466	0.99797	0.862

Note: The corresponding mathematical expectation of the number of working elements of RFS (3) is M_s=5.62

Table 6

Results of determining the probability of a working state of the system for each subsystem according to scheme (*d*)

State No., j	Number of simultaneous failures, l	Probability of a working state of the system			
		Reconnaissance, P_r	Control, P_c	Firing, P_f	Resultant, P_j
1	2	0.98145	0.53491	0.99797	0.524
2	1	0.98145	0.86466	0.99995	0.849
3	1	0.98145	0.86466	0.99995	0.849
4	3	0.98145	0.53491	0.99797	0.524
5	4	0.79251	0.53491	0.99797	0.423
6	1	0.99945	0.86466	0.99797	0.862
7	1	0.99945	0.86466	0.99797	0.862
8	1	0.99945	0.86466	0.99797	0.862
9	1	0.99945	0.86466	0.99797	0.862

Note: The corresponding mathematical expectation of the number of working elements of RFS (3) is M_s=5.59

$$P_{r,res} = 1 - \left(\begin{array}{l} 1 - \left(1 - \left(1 - P_1\right)\left(1 - P_2\right)\right) \times \\ \times P_4 \left(1 - \left(1 - P_6\right)\left(1 - P_7\right)\right) \end{array} \right) \times$$

$$\times \left(1 - \left(1 - \left(1 - P_2\right)\left(1 - P_3\right)\right) P_5 \left(1 - \left(1 - P_8\right)\left(1 - P_9\right)\right)\right). \quad (9)$$

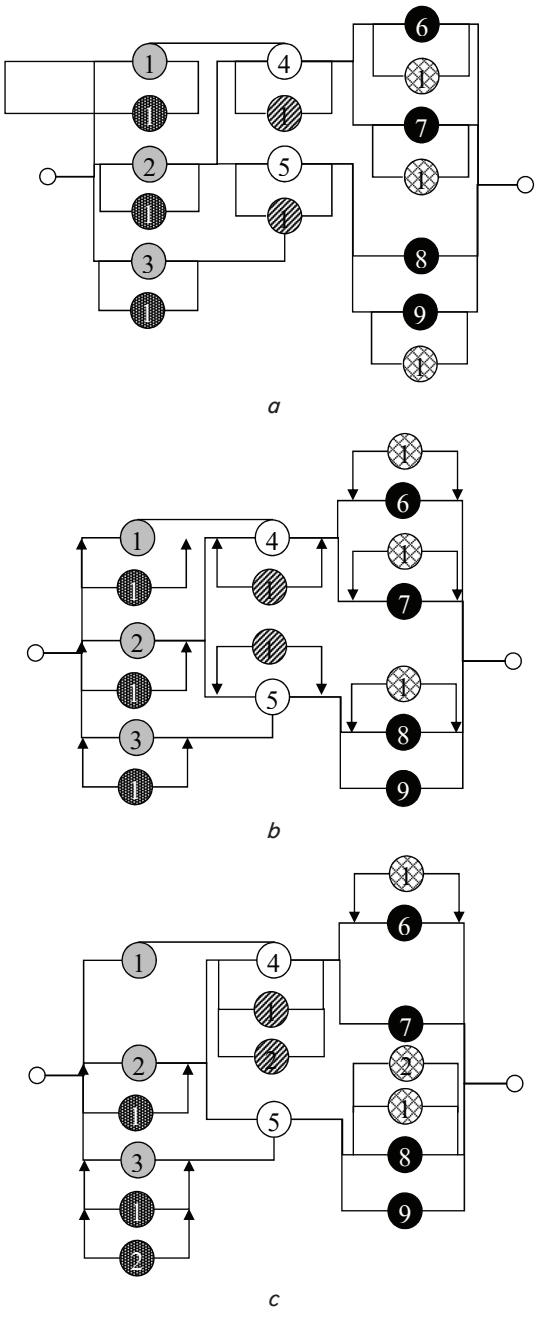

Fig. 5. General view of the RFS reliability schemes reserved in different variants: *a* — active redundancy; *b* — passive redundancy; *c* — mixed redundancy; ● — a separate structural-functional element of the intelligence subsystem; ◯ — a separate structural-functional element of the control subsystem; ● — a separate structural-functional element of the firing subsystem; ● — a separate structural-functional element of the redundant reconnaissance subsystem; ● — a separate structural-functional element of the redundant reconnaissance subsystem; ⊗ — a separate structural-functional element of the redundant firing subsystem; ○ — nodal point

Based on the formula for calculating the probability of trouble-free operation of the RFS with an active redundancy (1), the estimation dependence (9) takes the following form:

$$P(t)_{r,res}=1-\begin{pmatrix}1-\left(1-\left(1-\left(1-e^{-\lambda_r t}\right)^2\right)\right)^2\times\\ \times\left(1-\left(1-e^{-\lambda_c t}\right)^2\right)\times\\ \times\left(1-\left(1-\left(1-\left(1-e^{-\lambda_f t}\right)^2\right)\right)^2\right)\end{pmatrix}$$

$$\begin{pmatrix}1-\left(1-\left(1-\left(1-e^{-\lambda_r t}\right)^2\right)\right)^2\times\\ \times\left(1-\left(1-e^{-\lambda_c t}\right)^2\right)\times\\ \times\left(1-\left(1-\left(1-\left(1-e^{-\lambda_f t}\right)^2\right)\right)e^{-\lambda_f t}\right)\end{pmatrix}. \quad (10)$$

Applying the estimation dependence (2) to formula (9) for variant (*b*) in Fig. 5, the formula takes the following form:

$$P(t)_{r,res}=1-\begin{pmatrix}1-\left(1-\left(1-\left(e^{-\lambda_r t}\sum_{i=0}^{2}\frac{(\lambda_r t)^i}{i!}\right)\right)^2\right)\times\\ \times\left(e^{-\lambda_c t}\sum_{i=0}^{2}\frac{(\lambda_c t)^i}{i!}\right)\times\\ \times\left(1-\left(1-\left(e^{-\lambda_f t}\sum_{i=0}^{2}\frac{(\lambda_f t)^i}{i!}\right)\right)^2\right)\end{pmatrix}$$

$$\begin{pmatrix}1-\left(1-\left(1-\left(e^{-\lambda_r t}\sum_{i=0}^{2}\frac{(\lambda_r t)^i}{i!}\right)\right)^2\right)\times\\ \times\left(e^{-\lambda_c t}\sum_{i=0}^{2}\frac{(\lambda_c t)^i}{i!}\right)\times\\ \times\left(1-\left(1-\left(e^{-\lambda_f t}\sum_{i=0}^{2}\frac{(\lambda_f t)^i}{i!}\right)\right)\left(1-e^{-\lambda_f t}\right)\right)\end{pmatrix}. \quad (11)$$

Accordingly, for variant (*c*) in Fig. 7 formula (9), when using formulae (1) and (2), takes the following form:

$$P(t)_{r,res}=$$

$$=1-\begin{pmatrix}1-\left(1-\left(1-e^{-\lambda_r t}\right)\left(1-e^{-\lambda_r t}\sum_{i=0}^{1}\frac{(\lambda_r t)^i}{i!}\right)\right)\times\\ \times\left(1-\left(1-e^{-\lambda_c t}\right)^3\right)\times\\ \times\left(1-\left(1-e^{-\lambda_f t}\sum_{i=0}^{1}\frac{(\lambda_f t)^i}{i!}\right)\left(1-e^{-\lambda_f t}\right)\right)\end{pmatrix}$$

$$\begin{pmatrix}1-\begin{pmatrix}1-\left(1-e^{-\lambda_r t}\sum_{i=0}^{1}\frac{(\lambda_r t)^i}{i!}\right)\times\\ \times\left(1-e^{-\lambda_r t}\sum_{i=0}^{2}\frac{(\lambda_r t)^i}{i!}\right)\end{pmatrix}\times\\ \times e^{-\lambda_c t}\left(1-\left(1-\left(1-e^{-\lambda_f t}\right)^3\right)\left(1-e^{-\lambda_f t}\right)\right)\end{pmatrix}. \quad (12)$$

The calculation results for relevant conditions based on formulae (10) to (12) are given in Table 7.

Table 7

Results of determining the probability of trouble-free RFS functioning based on different schemes

Operation duration, h	Probability of trouble-free functioning of RFS with a certain type of redundancy		
	Active (*a*)	Passive (*b*)	Mixed (*c*)
5	0.087995	0.115044	0.15496
4.5	0.136276	0.181672	0.21927
4	0.229439	0.276118	0.30233
3.5	0.349689	0.400519	0.40425
3	0.504267	0.549267	0.5217
2.5	0.677637	0.705633	0.64711
2	0.836876	0.843764	0.76914
1.5	0.945184	0.939637	0.87473
1	0.991068	0.986395	0.95172
0.5	0.999695	0.999084	0.99206

Our results of analyzing the data given in Table 7 indicate that it is impossible, with any type of redundancy, to reach the level of the predefined probability of trouble-free operation. Therefore, we increased the multiplicity of redundancy for each element by 2 (Fig. 6). The calculation results are given in Table 8 and shown in Fig. 7.

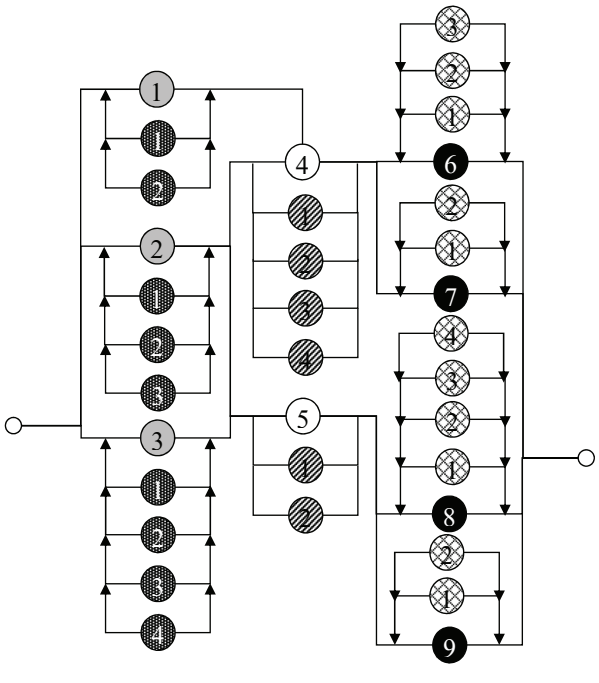

Fig. 6. General view of the RFS reliability scheme with mixed types of redundancy and with an increased multiplicity of redundancy by 2 for each element

Table 8 and Fig. 7 demonstrate the results from determining the probability of trouble-free RFS functioning according to various schemes with an increase in the multiplicity of the redundancy by 2. The type of RFS is three-component, that is, the specified system includes subsystems of reconnaissance, control, and firing. Moreover, our

calculations take into consideration the types of individual functional elements via the values of indicators of their characteristics. That is, except for the case given in the example, it can be applied to RFS for tactical, operational, or strategic purposes, as well as ground-, air-, or sea-based.

The conditions for modeling the RFS functioning under which we built graphic dependences in Fig. 7 include a military (combat) activity with an active counteraction by the enemy. The parameters of failure of individual functional elements of the subsystems of reconnaissance, control, firing are indicated in the initial data, based on the intensity of failures. The total number of reconnaissance, control, and firing means is also indicated in the input data. A feature of modeling is that a critical area was artificially created by reducing individual functional elements (a control subsystem). This is done to test the procedure for the ability to solve the task of determining the volume and type of redundancy in unbalanced systems.

Table 8

Results of determining the probability of RFS trouble-free functioning according to various schemes with an increase in the multiplicity of redundancy by 2

Operation duration	Probability of RFS trouble-free functioning with a certain type of redundancy		
	Active (*a*)	Passive (*b*)	Mixed (*c*)
5	0.212691	0.53254	0.81545
4.5	0.32161	0.65337	0.88846
4	0.46206	0.76653	0.94117
3.5	0.62308	0.86065	0.97393
3	0.77997	0.92859	0.99079
2.5	0.9019	0.96992	0.99759
2	0.9708	0.99027	0.99958
1.5	0.995375	0.99787	0.99996
1	0.99975	0.99977	0.99999
0.5	0.99999	0.99999	1

A general view of the algorithm of activities by officials when planning a mission is shown in Fig. 8.

Analysis of the algorithm of activities by officials when planning a mission (battle) reveals that the implementation of the procedure for justifying the type and volume of redundant RFS structural-functional elements would reduce uncertainty in planning. In addition, this procedure could optimize the number of means involved in reconnaissance, control, and firing under the conditions of a given activity (battle).

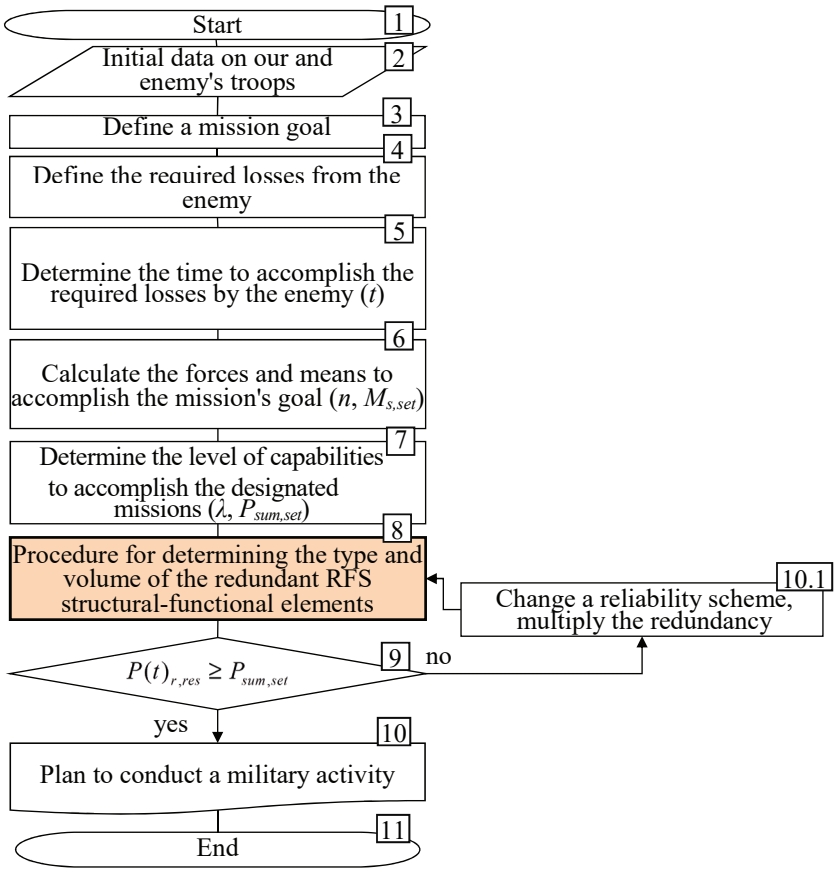

Fig. 8. The algorithm of activities by officials when planning an activity (battle) using the procedure for substantiating the type and volume of redundant RFS structural-functional elements

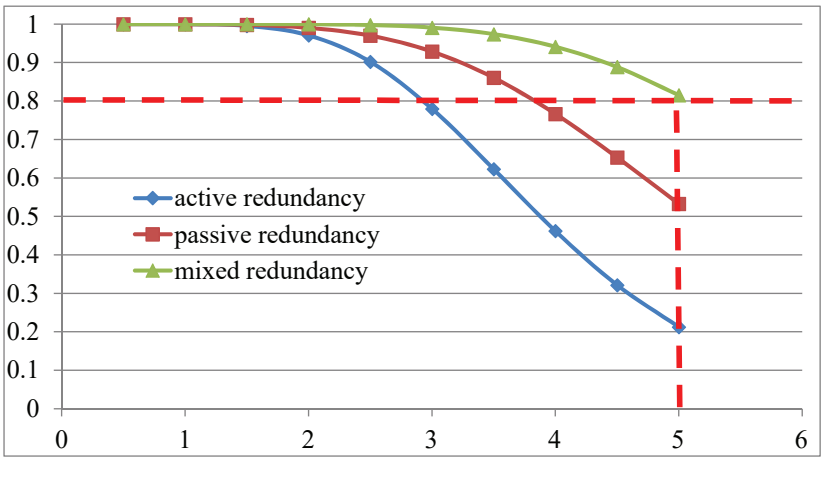

Fig. 7. Dependence chart of the probability of trouble-free operation with different types of redundancy on the operation duration

6. Discussion of results of devising a procedure for justifying the type and volume of redundant structural-functional elements

Our analysis of the results demonstrates that a set mission, in particular regarding the specified probability of RFS trouble-free functioning, is accomplished with a mixed type of redundancy. Moreover, when giving preference to passive redundancy, using active one only to critical elements – individual functional elements of the control subsystem. The advantage of a mixed type of redundancy over a passive redundancy is 28 %.

These results are explained by an integrated approach to considering the op-

erational patterns of each RFS subsystem. In addition, the difference between an active and passive redundancy is explained by the fact that the active redundancy remains under the influence of factors that can lead to failure. Such factors include operation duration, the influence of the enemy, the impact of operating conditions.

In general, when devising a procedure for determining the type and volume of the RFS redundant structural-functional elements, it was found that the methodology based on this procedure and the algorithm could provide for a justified choice of the type and volume of the RFS redundant structural-functional elements, taking into consideration the operational patterns of such systems.

The practical component of this study involves the use of the devised procedure for the justification of the type and volume of redundancy in the practical activities involving troops (military forces). This procedure should be directly used when planning a mission (activity). Thus, depending on the level of hostilities, input data are formed when determining the required degree of enemy defeat, which would make it possible to determine the time when this degree is achieved. Accordingly, it is possible to determine the time of the mission, which is the input value. In addition, the degree of damage to an enemy could determine the need for forces and means, which would form the initial data on the quantity of reconnaissance, control, and firing means. It would also make it possible to establish the level of the mathematical expectation of the number of working elements of RFS. The next stage implies the analysis of the capabilities of the means of reconnaissance, control, and firing of both our troops and the enemy, which could make it possible to determine the characteristics of the functioning of these systems. Generalizing the characteristics would help determine the intensity of failures of these means and the level of ability to perform tasks for their intended purpose, that is, to establish an acceptable level of the probability of RFS trouble-free functioning. The subsequent stage involves substantiating the type and volume of redundant means of RFS subsystems by using the procedure proposed in this work. Moreover, in case of not reaching the required level of the probability of RFS trouble-free functioning, the multiplicity of the redundancy is increased.

This paper has proposed an algorithm for substantiating the type and volume of the redundant RFS structural-functional elements, taking into consideration the operational patterns of such systems (Fig. 3). This algorithm is based on a combination of survivability assessment methods and reliability assessment methods. This combination aims to improve the effectiveness of these methods and reduce uncertainty in the calculations.

The special features of RFS application, which are taken into consideration in our procedure, include the accomplishment of different missions by individual functional elements (intelligence, control, firing). This feature has been taken into consideration by using the most appropriate types of redundancy (Fig. 1, 2, formulae (6) to (8)). Another feature is functioning under the conditions of the enemy's activity, which has been taken into consideration by checking the RFS survivability level before testing the reliability of operation (Table 1, formulae (3) to (5)).

The advantages of our algorithm are that determining the reliability of RFS functioning is performed in a comprehensive way involving a survivability check, which reduces uncertainty when considering RFS. In addition, the specified algorithm makes it possible to determine such a structural-functional scheme that would correspond to the specified levels of survivability and reliability of functioning (Fig. 3, units 7 and 11). In addition, our algorithm makes it possible to take into consideration various types of redundancy, in particular: active and passive redundancy (Fig. 3, unit 9).

Some limitations in using the algorithm for substantiating the type and volume of the RFS redundant structural-functional elements (Fig. 3) relate to that the algorithm is employed for the case when RFS hits a single target. That is, the purpose of RFS operation is to defeat one goal. Another limitation concerns the fact that all structural-functional elements within a certain subsystem are the same.

The disadvantage of this algorithm is the imperfection of the procedure for determining the importance of individual organizational and functional elements of subsystems. That is, the importance of these elements must be determined by using another technique, which, in some ways, complicates the work. However, that may be addressed in further research.

The next task of the study was to devise a procedure for determining the type and volume of the RFS redundant structural-functional elements. The result is the selected most appropriate type of redundancy – mixed (Fig. 6, 7, Table 8). This finding is based on the application of the algorithm for substantiating the type and volume of the RFS redundant structural-functional elements and the combination of methods for assessing survivability and methods for assessing the reliability of functioning.

Overall, our results make it possible to overcome the issue related to significant uncertainty when choosing the type and volume of redundancy.

The advantage of these results is the ability to quantify the advantage of a certain type of redundancy over another (Fig. 7, Table 8).

The limitation is that these results can only be applied to the conditions described in the conditions. Investigating other variants of RFS structural-functional schemes could make it possible to compile a statistical sample for generalized conclusions. This may be a further direction of research.

The disadvantage is that our results do not take into consideration other subtypes of redundancy, in particular, majoritarian, sliding, etc.

In general, the totality of these results indicates the development of a procedure for justifying the type and volume of the RFS redundant structural-functional elements, taking into consideration the operational patterns of such systems. This procedure includes the algorithm (Fig. 3), as well as methods for assessing survivability and methods for assessing the reliability of functioning. This procedure has been tested for performance by considering an example of the justification of the type and scope of redundant structural-functional elements of RFS (Fig. 6, Table 8) that produced an adequate result (Fig. 7), confirmed by the practical application of RFS in recent armed conflicts.

In general, such a scientific result makes it possible to overcome the shortcomings that had been found both in the practical and theoretical aspects.

To add to the advantages of this methodology, it is necessary to indicate its relative simplicity. This procedure could be used without additional formalization for the consumer. In addition, a given procedure does not require any special skills of the researcher for its use. In addition, the advantage of this procedure is its modularity, that is, the possibility to

replace certain units with others, more appropriate for the conditions of a particular mission.

The limitation of using this procedure is that it can be used for the case when RFS hits a single target. Another limitation is that within the subsystem individual functional elements have the same parameters. In addition, the constraint is that the time required to activate a redundancy element is close to 0. One important limitation is that the flow of failures is subject to the exponential law of distribution of random variables.

In general, regarding the shortcomings of our procedure, it should be noted that it takes into consideration a certain set of types of redundancies, which, to some extent, limits researchers. In addition, the disadvantage of this procedure is that the importance of each individual functional element must be determined separately. In general, overcoming these shortcomings may be the area of further research.

7. Conclusions

1. We have proposed the algorithm for substantiating the type and volume of the redundant RFS structural-functional elements, taking into consideration the operational patterns of such systems. Its essence is the structuring of steps to assess the survivability of the RFS, and, based on the chosen option, the estimation of the operational reliability of such a system. The special features of this algorithm are to take into consideration the characteristics of individual RFS subsystems such as control, reconnaissance, firing. A distinctive feature of this algorithm is the combination of methods for assessing survivability and methods for assessing the reliability of systems functioning, which would eliminate the shortcomings of these methods. In particular, uncertainty in the formalization of input data, high computational complexity. The scope of this algorithm is substantiating the types and volumes of certain redundant RFS functional elements when planning military (combat) activities.

2. A procedure for determining the type and volume of the redundant RFS structural-functional elements has been proposed. In addition, the most appropriate type of redundancy for accepted conditions has been determined – mixed, with a multiplicity of redundancy of individual functional elements not lower than 2. Under the accepted conditions, the difference between a mixed type of redundancy and a passive redundancy is 28 %. The distinctive feature of this result is its quantitative value. Due to this feature, we managed to overcome the issue related to the inability to determine the justified advantage of a certain type of redundancy of RFS individual functional elements over another. The scope of application of our result is the practical activities by commanders (chiefs) when planning military (combat) missions.

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